Development of a Prototype Robot Manipulator for Industrial Pick-and-Place Operations

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***Abstract*--** **In the industry today, continuous attempts to realize optimal efficiency and increased productivity have spawned much progress in the use of intelligent automated devices and machines to perform various operations and tasks. The thrust of this work is to present the development of a three-degree-of-freedom revolute robot manipulator amenable to pick-and-place operations in the industry. Appropriate kinematic equations of the manipulator are obtained, and then used to develop algorithms for locating predetermined positions of a small object in a customized workspace. An Arduino-based controller circuit is built to implement the algorithms, and servomotors are used to carry out independent joint control of the manipulator. The positions of the object are identified with the aid of light-dependent resistors (LDR). Besides, in order to aid easy fabrication of links and overall system assembly, a 3D model of the manipulator is designed. The results of the work, showing effective and satisfactory operation of the manipulator, are presented.**

***Index Term*— Arduino® controller, end-effector, kinematic analysis, links and joints, pick-and-place operation, robot manipulator**

I Introduction

Following the Karel Capek's drama, R.U.R. (Rossum's Universal Robots), in which automatons in human form carried out arduous tasks [1], robots made their industrial debut in 1960s [2]. Since this advent of robots in the industry, numerous and multifaceted research and development strides in robotics have been witnessed [3, 4, 5, 6, 7, etc.]. Also, as the world continues to engage in intense and sophisticated technological operations and activities, such as space and underwater explorations, assembly plant automation, delicate machine-assisted surgical operations, etc., human dependence on robots and, in many specific applications, robot arms has increased significantly.

A robot, according to the Robot Institute of America, is "A reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks." Therefore, because of their re-programmability and adaptability, robots are suited to many requirements or applications associated with industrial tasks [8]. In fact, robots are particularly useful in many industrial applications which are laborious, boring, and hazardous. And several types of robot manipulators have been developed in times past; examples of these are the The Tomorrow Tool (T^3), introduced by Cincinnati Milacron, Inc. in 1974, the Programmable Universal Manipulator for Assembly (PUMA) developed by Victor Scheinman at the pioneering robot company Unimation, the Selective Compliant Articulated Robot for Assembly (SCARA), the AdeptOne robot by Adept Technology, Inc., the Shuttle Remote Manipulator System (SRMS), etc. One of the vitally important functions of a robot manipulator in the industry is a pick-and-place operation, such as, lifting a payload from within its work space, carrying it to a predetermined position and then releasing it. For instance, Sanjay Lakshminarayan et al. [9] worked on "Position Control of Pick and Place Robotic Arm," which is a 5-DOF articulated robot arm for real-time molding machine operation; Karl Berntorp et al. [10] proposed the application of a mobile robot with kinematic redundancy for future pick-and-place operation in the grocery stores; Binbin Lian et al. [11] showed how the dimensional parameters of a two-degree-of-freedom parallel manipulator could be optimized to realize high-performance pick-and-place operation; in order to obtain effective pick-and-place operation, Altuzarra O. et al. [12] proposed two design methods for a mechanical drive which would yield an increased end-effector angular range; and Bin Liao et al. [13] carried out an optimal design of a three-degree-of-freedom planar revolute-chain parallel manipulator with a view to improving its operational velocity and accuracy for pick-and-place tasks.

The crux of this paper is to design and construct a three-degree-of-freedom revolute robot manipulator, which would identify the presence of a payload – using light-dependent resistors as field sensors – and then reach the position of the payload, pick it up and motion to the predetermined final position and then release the payload before returning to its home position to await another signal of a payload presence. The rest of the paper is organized as follows. Section II gives a structural representation of the manipulator, outlining its kinematic and moment equations. The design and construction of the manipulator are discussed in Section III, while Section IV presents the complete system and the observations made when it is tested. And a conclusion showing recommendations and direction for future work is drawn in Section V.

II System Analysis

The robot manipulator developed in this work is a three-degree-of-freedom (DOF) revolute arm, which has three links ending in an end-effector shaped to pick a small object. The structure of the revolute arm, adapted from [14], is shown in Fig. 1. This structure will be used to derive the kinematic and moment equations of the arm.

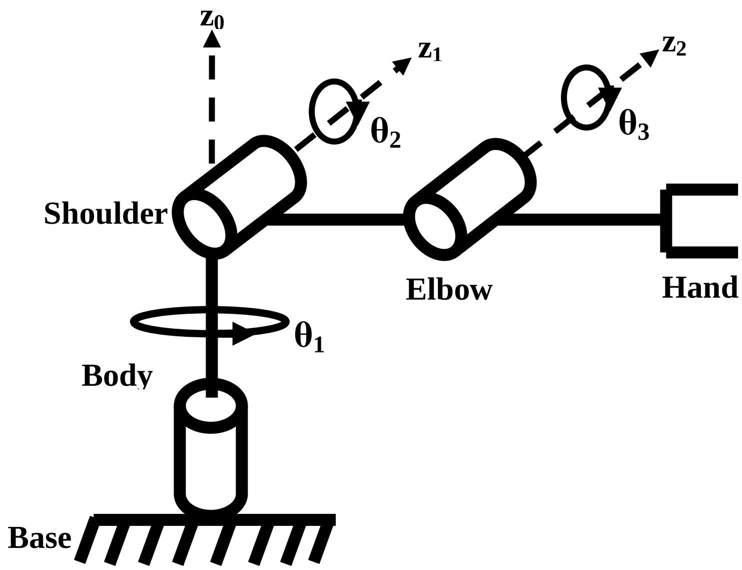


Fig. 1. Structural diagram of a revolute arm

- **Kinematic Equations**

The kinematic analysis of the robot arm deals with the relationships between the end-effector's variables (i.e., the position and orientation) and joint variables (i.e., the rotational and/or translational displacements). Whereas the equations describing the position and orientation of the end-effector in terms of the given joint variables and link lengths are termed forward kinematic equations, the corresponding equations expressing the joint variables in terms of the position and orientation of the end-effector and link lengths are called inverse kinematic equations. A kinematic cycle showing these relationships is depicted in Fig. 2.

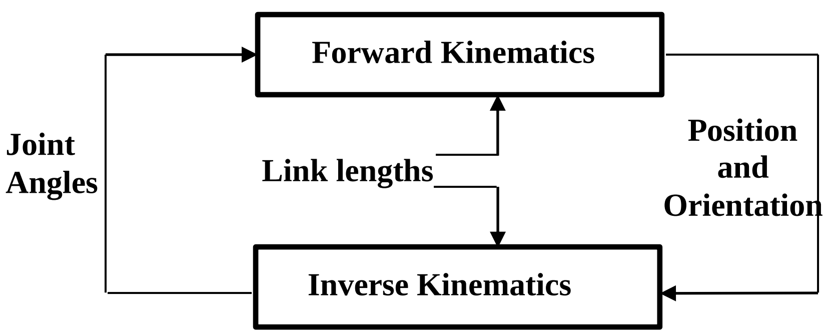


Fig. 2. Kinematic cycle showing forward and inverse kinematics

The method employed here to solve the kinematic problem is the Denavit-Hartenberg (DH) method [14]. It is a methodical approach for computing the homogenous transformation matrix of a robot manipulator in terms of four distinct parameters, which are Θ_i (the rotation of joint i about the z-axis), a_i (the translation along the x-axis between joints i and $i+1$), d_i (the translation along the z-axis between joints i and $i+1$), and α_i (the rotation about the x axis), where i is an index number for the joint or link . This matrix, which gives the position and orientation of the end-effector of the robot explicitly, and can also be solved analytically to obtain the joint angles, is given as [14, 15]

$$T_i = \begin{bmatrix} c_{\theta i} & -s_{\theta i}c_{\alpha i} & s_{\theta i}s_{\alpha i} & a_i c_{\theta i} \\ s_{\theta i} & c_{\theta i}c_{\alpha i} & -c_{\theta i}s_{\alpha i} & a_i s_{\theta i} \\ 0 & s_{\alpha i} & c_{\alpha i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $c_{\theta i} = \cos\theta i$, $s_{\theta i} = \sin\theta i$, etc. Therefore, for the robot arm in Fig. 1, with the associated frame designation shown in Fig. 3, the DH parameters are displayed in Table I.

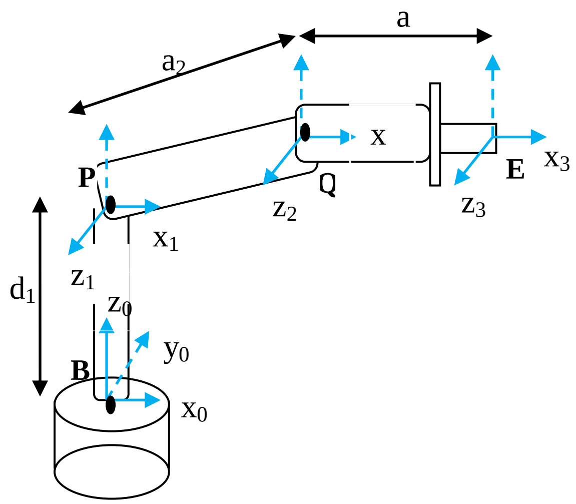


Fig. 3. Robot manipulator showing link frames and parameters

Table I
DH parameter values

Link i	θ_i	d_i	a_i	α_i
1	θ_1	d_1	0	-90^o
2	θ_2	0	a_2	0
3	θ_3	0	a_3	0

Therefore, the overall transformation matrix, T_{B-E}, of the end-effector frame to the base frame can be computed as

$$T_{B-E} = \begin{bmatrix} c_1(c_2c_3 - s_2s_3) & -c_1(s_1c_2 - c_1s_2) & s_1 & c_1(a_3(c_2c_3 - s_2s_3) + a_2c_2) \\ s_1(c_2c_3 - s_2s_3) & -s_1(s_1c_2 - c_1s_2) & c_1 & s_1(a_3(c_2c_3 - s_2s_3) + a_2c_2) \\ (s_2c_3 - c_2s_3) & c_2c_3 - s_2s_3 & 0 & -a_3(s_2c_3 + c_2s_3) - a_2s_2 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where $c_1 = \cos_{\theta 1}$, $s_1 = \sin_{\theta 1}$, etc.
From eqn (2), the coordinates, p_x, p_y, p_z, of the tip of the end-effector are

$$p_x = c_1(a_3(c_2c_3 - s_2s_3) + a_2c_2) \quad (3)$$

$$p_y = s_1(a_3(c_2c_3 - s_2s_3) + a_2c_2) \quad (4)$$

$$p_z = -a_3(s_2c_3 + c_2s_3) - a_2s_2 + d_1 \quad (5)$$

The home position of the robot is obtained when all the joint angles are equal to zero, i.e. $\Theta_1 = 0$, $\Theta_2 = 0$, and $\Theta_3 = 0$. Hence, the home position coordinates are $p_x = a_3 + a_2$, $p_y = 0$, and $p_z = d_1$.
Likewise, by solving eqns. (3)-(4) analytically, the joint angles, Θ_1, Θ_2, and Θ_3, are found as

$$\theta_1 = \tan^{-1}\left(p_y / p_x\right) \quad (6)$$

$$\theta_2 = \cos^{-1}\left[\frac{\left(c_1p_x + s_1p_y\right)\left(a_3c_3 + a_2\right) + a_2s_3\left(d_1 - p_z\right)}{\left(a_3c_3 + a_2\right)^2 + a_3^2s_3^2}\right] \quad (7)$$

$$\theta_3 = \cos^{-1}\left[\frac{\left(c_1p_x + s_1p_y\right)^2 + \left(d_1 + p_z\right)^2 - \left(a_2^2 + a_3^2\right)}{2a_2a_3}\right] \quad (8)$$

- **Moment Equations**

In order to establish the likely load capacity of the robot, that is, the maximum load weight that the robot can sustain, the required torque for the respective joints must be determined. To do this, the moments required at each joint must be calculated and then used to select the appropriate motor size to offset it. Fig. 3 shows the force diagram of the robot manipulator, which is employed to compute the moments M1 and M2 at the shoulder and elbow joints, respectively. Other parameters shown in the figure depict the dimensions (which are given in Section III) of the links and the weight for each of the components of the robot (links and motors).

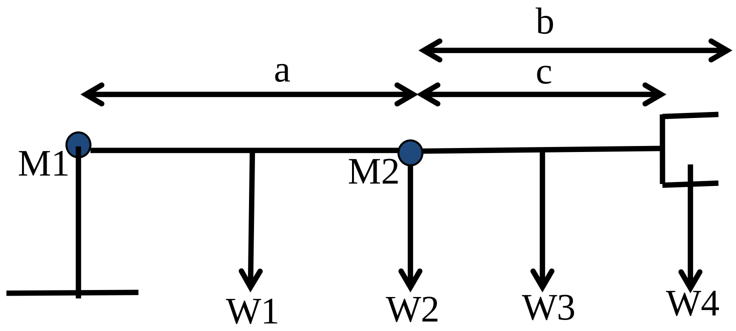


Fig. 4. Robot manipulator force diagram

These moments are calculated respectively as

$$M1 = (W1 \times a/2) + (W2 \times a) + (W3 \times [a + c/2]) + (W4 \times [a + b]) \quad (9)$$

and

$$M2 = (W3 \times c/2) + (W4 \times b) \quad (10)$$

III SYSTEM DESIGN AND CONSTRUCTION

Development of the arm requires that all its various parts and subsystems are identified and then treated separately. This offers a holistic approach to the complete implementation of the arm. Therefore, the design and construction of the arm are considered in three major parts: the mechanical hardware, the electrical hardware, and the controller software.

- **Mechanical hardware**

The mechanical part of the system encompasses the entire physical structure and how it is fitted to implement the operation, and this includes the base of the arm, the links and joints, and the gripper. The design of this physical structure, in terms of dimensions, is done [16] based on the desired effective workspace for the robot manipulator by using AutoDesk (see Fig. 5). The overall specifications of the robot structure are shown in Table II.

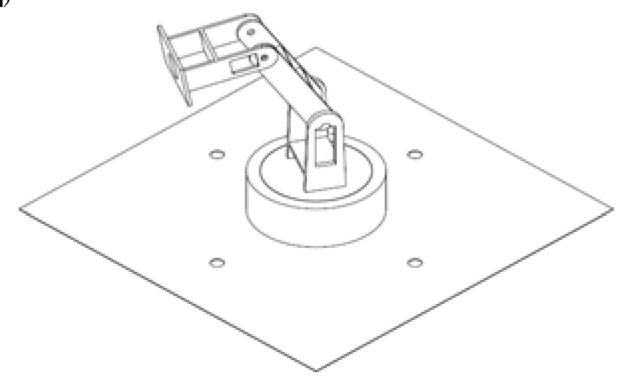


Fig. 5. Structural design of the robot arm

Table II
Link and base specifications of the robot arm

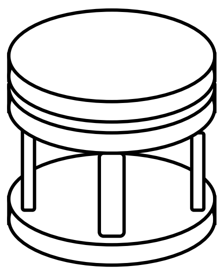
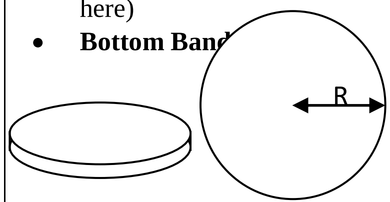
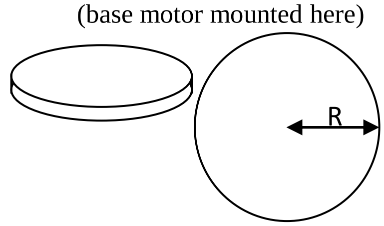
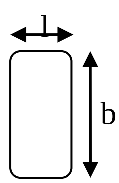
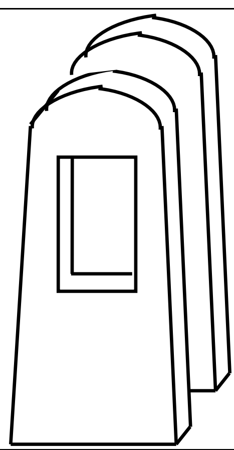
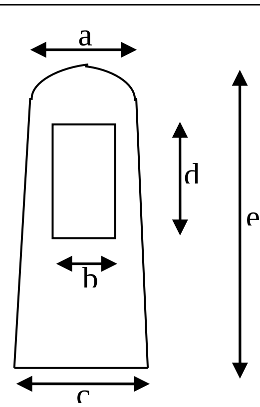
#	Component	Sub-component	Dimension/weight
1		• **Top Band** (the shoulder link will rest here) • **Bottom Band** 	Radius, R = 150mm Thickness = 8mm
		• **Mid Band** (base motor mounted here) 	Radius, R = 150mm Thickness = 5mm
			Length, l = 55mm Breadth, b = 20mm Thickness = 8mm

Table II cont.

#	Component	Sub-component	Dimension/ weight
2			a = 50mm b = 32mm c = 62mm d = 70mm e = 130mm Weight W1 = 750g

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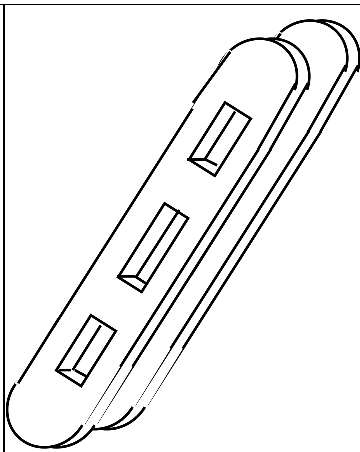
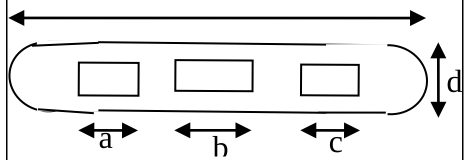
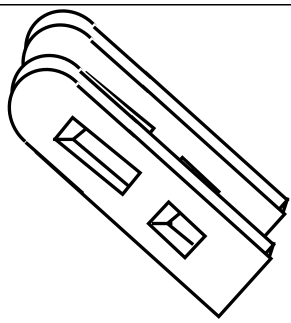
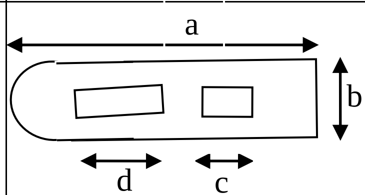
3			a = 20mm b = 40mm c = 20mm d = 43mm e = 200mm Thickness = 5mm Weight W2 = 146g

Table II cont.

#	Component	Sub-component	Dimension/weight
4			a = 120mm b = 40mm c = 20mm d = 40mm Thickness = 5mm Weight = 86g

Further, with the dimensions shown in Table II, a maximum moment of 23.0kg.cm at M1 and 7.5kg.cm at M1 (using eqns. (9) and (10)) can be realized. These moments are calculated based on a maximum load capacity (220g) of the motors used. In addition, the material selected to build the links and the base of the robot arm is Plexiglas [17]. It is a transparent thermoplastic with a melting point of 160^{o}C and a density of 1.18g/cm^{3}. This material is chosen because it is light-weight, shatter-resistant, easily available, machine-able, and can withstand the weight of the motor as well as the objects that would be picked by the gripper.

- **Electrical hardware**

  The various parts involved in the electrical subsystems are the power supply unit, the controller unit, the actuating unit, the sensing unit, and the display unit. These are discussed below *seriatim*.

  (a) The power supply unit:

  The electrical subsystems require a constant DC voltage before they can operate. But, in order to mitigate the limitations that come with using a DC battery, a dual-mode (fixed and variable) regulated power supply unit is designed and used. The power supply circuit is made up of a transformer (with a 240/12-VAC, 1000-mA, 50-Hz rating), a bridge rectifier (which gives about a 12-V direct current output), two smoothing capacitors (a 6800-µF capacitor connected in parallel to the output of the rectifier circuit before the fixed voltage regulator, and a 0.1-µF capacitor connected after the fixed voltage regulator) [18], a 9-V fixed voltage regulator, and a variable voltage regulator (5-8V). Suffice to say that the first voltage level provides the voltage for the Arduino Uno board, while the second voltage level provides a voltage range to be used to supply the differently rated servo motors.

  (b) The controller unit:

  This is the heart of the robot system, as all vital kinematic and control calculations are performed by it. The controller unit employed in this work is an Arduino Uno board. It operates on Atmega328 microcontroller and has 14 digital input/output pins (6 of which can be used as PWM outputs), 6 analog inputs, a 16-MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. The unit receives field information (signals) from the sensors and then processes it based on the already-programmed software in its memory. Actually, a pin (configured as an input pin) on the microcontroller is connected to the sensor conditioning circuit, and the microcontroller responds depending on whether this pin is HIGH or LOW. When the pin is HIGH, it means there is presence of an object, and the microcontroller uses a pulse width modulated signal to control the joint servo motors to drive the robot to an appropriate location (the object position in this case) in the workspace, but when the pin is LOW, it means there is absence of an object, and the microcontroller maintains the robot at its home position. Besides, the controller unit controls the display of information on the LCD display and on the indicator LEDs.

(c) The actuating unit:

The actuators that are being implemented for the joint operation are servomotors. Because the robot is a revolute manipulator, it means all the joint variables are angle rotations, and therefore, the servomotors are very suitable. Conventional RC servo motors consist of 4 primary parts: a DC motor, a gearbox/system, a potentiometer, and a control circuit. The servomotor is controlled by a pulse width modulated signal (control signal) from the controller unit through its control wire.

(d) The sensing unit:

The sensing unit is a voltage divider circuit which has a light-dependent resistor as the output element. The light-dependent resistor functions such that its resistance is inversely proportional to the light flux incident on it. Hence, the unit operates such that when the object to be picked is placed over the sensor, a HIGH signal is sent to the controller, signifying that the object is present. When the object is lifted or absent from that position, the output of the circuit is LOW.

(e) The display unit:

For the display unit, a 16 X 2 LCD, 3 LED indicators, and two pushbutton switches are employed. The purpose of this is to achieve a proper human-machine interface so that the operation status, system errors and other vital information can be reported and displayed.

The complete electrical circuit diagram is shown in Fig. 6, while its implementation on a Vero board is displayed in Fig. 7.

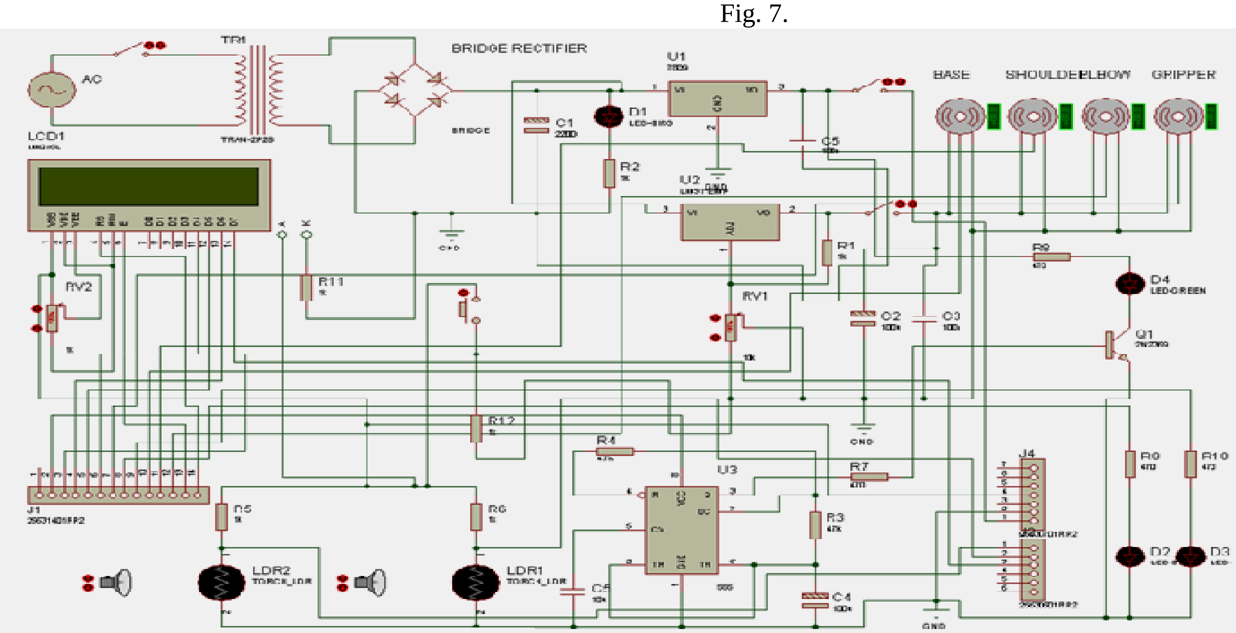


Fig. 6. Complete eletcrical wiring diagram

Fig. 7. Picture of the complete electrical circuitry

Controller software

The robot software can be regarded as the soul of the robot manipulator because it directs and coordinates the entire robot operation. There are many possible choices for the programming language platforms to employ in the development of the robot software, but use is made of the Arduino board here for ease of operation. The code is written within the Arduino IDE. Fig. 8 is a flowchart that describes the software algorithm.

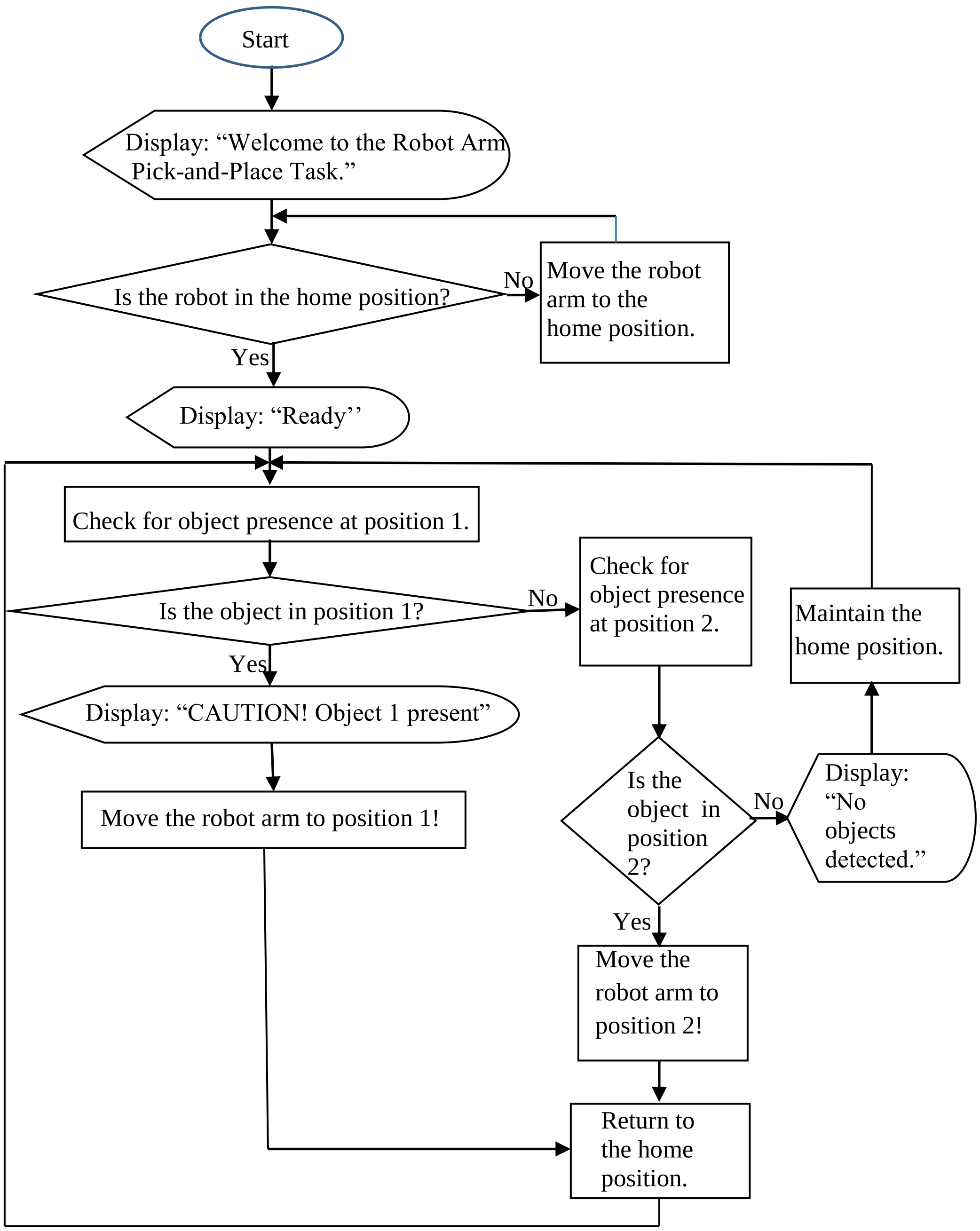


Fig. 8. Flowchart for the computer program

IV SYSTEM TESTING AND OBSERVATION

Fig. 8 shows the complete assembly of the manipulator. The robot works satisfactorily well when tested. Two pre-programmed positions in the workspace are used to test its operation—one position represents the coordinates of the location of the target object, while the other position captures the home location where the object is placed after it is picked. But the primary observation made is the jerking of the servomotors when they are actuated. The low- capacity servos demonstrate greater jerking, especially when the high-capacity ones are being actuated. These vibrations, caused by the transients in the power line, affect the robot adversely. But connecting capacitors in parallel to the servos reduce the jerking appreciably.

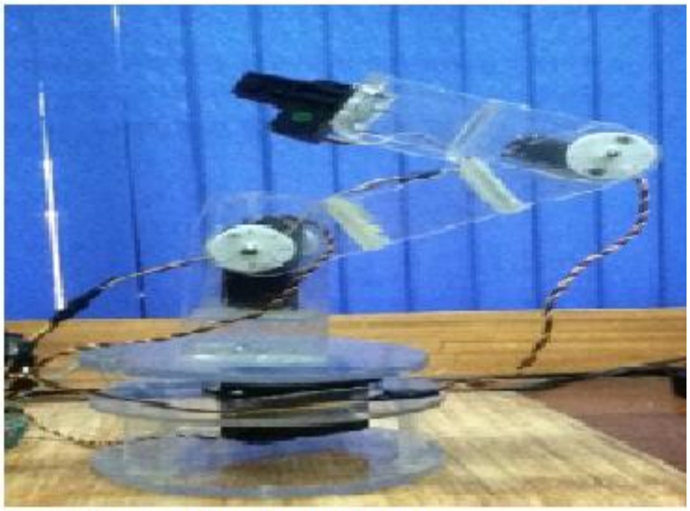


Fig. 9. Picture of the robot manipulator

V CONCLUSION

The construction of a robot arm for simple pick-and-place operations has been considered in this paper. The system hardware and software have been highlighted and discussed, and tests carried out on the complete assembly shows that the implementation is satisfactory. In order, however, to obtain an optimum grip pressure on the target object, it is recommended that a pressure sensor be incorporated and installed on one of the end-effector's fingers. Besides, a video camera and a computer with image processing capability can be used to give arbitrary locations of the object (instead of the pre-programmed positions employed in this work). Also, this work uses the independent joint control method for the pick-and-place operations. Thus, to make the manipulator more accurate and precise, future work, which the authors are currently looking at, will involve the use of computed torque control method.

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